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Scale Lengths in Disk Surface Brightness as probes of Dust Extinction in 3 Spiral Galaxies: M 51, NGC 3631 and M 100

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ABSTRACT

We have measured the radial brightness distributions in the disks of three nearby face-on spirals: M 51, NGC 3631, and NGC 4321 (M 100) in the photometric bands B through I , with the addition of the K band for M 51 only. The measurements were made by averaging azimuthally, in three modes, the two-dimensional surface brightness over the disks in photometric images of the objects in each band: (a) over each disk as a whole, (b) over the spiral arms alone, and (c) over the interarm zones alone. From these profiles scale-lengths were derived for comparison with schematic exponential disk models incorporating interstellar dust. These models include both absorption and scattering in their treatment of radiative transfer. The model fits show that the arms exhibit greater optical depth in dust than the interarm zones. The average fraction of emitted stellar light in V which is extinguished by dust within 3 scale-lengths of the center of each galaxy does not rise above 20% in any of them. We show that this conclusion is also valid for models with similar overall quantities of dust, but where this is concentrated in lanes. These can also account for the observed scale-lengths, and their variations.

Subject headings: ISM: dust extinction - galaxies, individual: M5 1 - galaxies, individual: NGC 3631 - galaxies, individual: NGC 4321 - galaxies: photometry - galaxies: spiral

1. Introduction

Photometric mapping of spiral galaxies yields both detailed morphology and a set of global physical parameters. Azimuthally averaged profiles of the surface brightness can usually be decomposed into a central bulge and an exponential disk, whose relative importance is a function of morphological type. In this paper we will concentrate on the properties of the disks which will be characterized by their observed exponential scale-lengths. From the fairly extensive detailed studies which have been published to date some general conclusions have been drawn which are still subject to empirical and theoretical debate. Most spiral galaxies have disks with a broadly exponentially declining radial surface brightness distribution (e.g. Kent 1984, de Jong 1995). It seems to be emerging that the scale-lengths observed tend to decrease systematically, but not strongly, with increasing wavelength, an effect which can be attributed to extinction by moderate amounts of dust, with radial metallicity gradients as a possible contributing factor (Elmegreen & Elmegreen 1984; Prieto *et al.* 1992; Evans 1994; Peletier *et al.* 1994, Beckman *et al.* 1995, de Jong 1995). The disk surface brightness extrapolated to the axis of a galaxy, μ_0 , lies within a narrow range, for a given photometric band, which for the B band is $\mu_0 = 21.6 (\pm 0.3)$ mag arcsec $^{-2}$ (Freeman 1970). For bands further into the red the range is larger, and the central disk surface brightness depends more strongly on spectral type (Peletier *et al.* 1994). These studies of disks have used one-dimensional, azimuthally averaged profiles to derive the parameters cited above. Galaxy disks are not, however, axisymmetrical; they almost invariably show structures, such as arms and bars. It is obvious from inspection of galaxy images that the arm surface brightnesses are higher at all optical and NIR wavelengths than those of the inter-arm zones of the disk, that arms often have dust lanes at their edges, and that the arms are sites of more concentrated star formation. Because of the latter two conditions, the brightness profile of the interarm zones may well be a more faithful tracer of the underlying stellar mass distribution, and thus offer a more appropriate way to determine the properties of the exponential disk. In an azimuthally averaged profile of a complete galaxy disk the arm contribution may well be dominant, especially in the shorter wavelengths, B and V bands. Dust will affect the arms and the interarm disk to different degrees at different wavelengths, and with different geometries. For these reasons we considered it a valuable exercise to separate the arms from the inter-arm zones, and to perform separate profile analyses. In a related paper (Knapen & Beckman 1996), radial profiles in several gas and star formation tracers were studied in detail for NGC 4321, for arm and interarm regions separately, with special emphasis on the role of the atomic hydrogen in the massive star formation process. In the present paper we concentrate on dust, and present our results for three well-studied nearby late-type spirals: M 51 (NGC 5495), NGC 3631, and NGC 4321 (M 100). In Section 2 we describe the data sets we used, and the methods of analysis applied, in Section 3 we present the observational results, which we compare, in Section 4, to the predictions of a set of theoretical models which incorporate absorption and scattering in their extinction parameters. In Section 5 we draw conclusions, and deal semi-quantitatively with the consequences of departures from homogeneously exponential radial dust distributions.

2. The data and its treatment

The observations were obtained from three different sources: two of the galaxies were observed specifically for the purpose of the present study, while for the third we used an existing set of images. For M 51 we used images in the B , R , and I optical bands kindly supplied to us by H.-W. Rix. The acquisition

and reduction of these images is described by Rix and Rieke (1993). They cover the inner disk of the galaxy out to a brightness level of $\mu_B = 23$ mag arcsec $^{-2}$, in the B band, with a scale of 1.78 arcsec pixel $^{-1}$. The images in B , V , R and I of NGC 3631 were obtained in service time at the Cassegrain focus of the 1m Jacobus Kapteyn Telescope (JKT) on La Palma, in January 1994, by P. Rudd and M. Asif. They were taken with a 1280×1180 pixel EEV CCD camera, with pixels subtending $0.31''$, which implies a field of view of some $6' \times 6'$. This is satisfactory to cover the galaxy down to $\mu_B = 24$ mag arcsec $^{-2}$, as NGC 3631 is not especially large in angle. We obtained B , V , R and I images of NGC 4321, also in service time, at the prime focus of the 2.5m Isaac Newton telescope (INT) on La Palma. The basic reduction of the images was described in Knapen *et al.* (1993). Photometric calibration was performed via aperture photometry from the literature. For NGC 3631 we only found aperture photometry in the V -band. The other colors were calibrated assuming at $r=100''$: $B - V = 0.70$, $V - R = 0.45$ and $R - I = 0.50$. NGC 4321 was calibrated using aperture photometry in B , and assuming at $r=100''$: $B - V = 0.90$, $V - R = 0.55$ and $R - I = 0.65$. In Plate 1 we present real color images of the three galaxies, produced by combining the images in B , V and I (B , R and K for M 51). In order to extract the radial profiles we first removed bright foreground stars from our images, defining the areas affected by the stars, and replacing the pixel values by blanks. The next step was to produce, for each galaxy and in each band, two separate images, one consisting only of the arm regions and the other of the inter-arm regions. To do this we first made a fit to the radial profile of the I -band image by azimuthally averaging the light in elliptical annuli, whose axes and ellipticities followed those of the disks as a whole. We then defined the arms as the regions in which the intensity was more than 7% larger than the fitted profile value. The complexity of the inner parts of the galaxies (out to some $20\text{-}30''$ from their nuclei) led us to define the arms here in the same way. Also at large radii the definition of the arms was slightly revised interactively. Since placing the boundary between arm and inter-arm regions is somewhat subjective at least two authors checked the procedure independently, with very good agreement in each case. We used the I band to produce a mask separating the arms from the inter-arm zones in the images of all the bands, because it was the reddest band available in all three galaxies, and allowed the clearest definition, minimizing the effects of patchy dust, and of local star formation. In Fig. 1 we show the mask separating arm from interarm images for M 51, in Fig. 2 we show the mask for NGC 3631, and in Fig. 3 we show the mask for NGC 4321, in all cases overlaid on the B -band image of the galaxy.

We used the three images (total disk, arm, inter-arm) in each band for each galaxy as inputs for the profile-fitting program Galphot (see Jørgensen *et al.* 1992). The program yields azimuthally averaged surface brightness profiles by fitting ellipses to a two-dimensional brightness distribution. For each galaxy surface profiles were calculated on elliptical isophotes. The ellipticity and position angle of these isophotes was constant for NGC 4321 (resp. 0.37 and 25°) and NGC 3631 (resp. 0.06 and 25°). For M 51 we let the ellipticity increase linearly from 0.1 at the center to 0.25 at $r = 50''$ and kept it at 0.25 for larger radii. Here the position angle was fixed at 140° . These values were determined on the basis of average photometry of the whole disk determined during an initial fit in I , where the ellipticity and position angle were left free.

The same isophotal geometry was employed for all three images of each galaxy in a given band. Finally radial surface brightness profiles were produced for the whole galaxy, for the arms alone, and

Fig. 1.— **Plate 1:** Composite plates produced by combining the B, V and I images of each of the three galaxies: Upper image (larger) NGC 4321, Lower left image M 51 (using B , R and K), Lower left image NGC 3631. These representations are effective in bringing out the distribution of dust in lanes associated especially with the spiral arms (dusky reddish features), as well as the blue star-forming zones.

for the interarm disks separately. These profiles were used to fit radial scale-lengths to the disk in the various bands. Since the bulges in all of these three galaxies are small compared to the disks, no bulge-disk decomposition procedure was adopted, but the inner limiting radius for measuring each disk profile was taken well outside the bulge. The same inner and outer radial limits were taken in all wavelengths when making the least squares fits to derive the scale-lengths for a given galaxy, as indicated explicitly in Table 1. Also given in Table 1 are the formal errors from the least squares fits. For a given range these errors are realistic. However, scale-lengths can vary considerably with adopted range, as will later be shown for NGC 4321, and can vary by factors up to 2. Fortunately, scale-length *ratios* are much less range-dependent.

Table 1: Observationally derived scale-lengths, in the photometric bands indicated, for the arm, interarm, and whole disk images of each of our three galaxies. Radial ranges for the measurements are included.

Galaxy	Phot. Band	Scale length (")					
		Total	±	Arm	±	Interarm	±
M 51	<i>B</i>	108. 1	14.9	154. 2	26.8	92. 8	9.4
	<i>R</i>	91. 2	8.9	118. 0	11.7	81. 2	7.0
	<i>I</i>	88. 5	7.4	110. 1	8.5	80. 4	6.1
	<i>K</i> 45" -250"	87. 4	5.7	98. 7	7.1	87. 1	6.8
NGC 3631	<i>B</i>	53. 2	5.7	67. 3	5.7	49. 1	3.6
	<i>V</i>	49. 4	3.9	58. 5	3.5	46. 5	2.6
	<i>R</i>	47. 6	3.4	54. 0	3.1	45. 1	2.3
	<i>I</i> 21" -110"	41. 6	2.6	47. 8	2.3	39. 2	1.8
NGC 4321	<i>B</i>	70. 4	2.2	76. 3	2.8	60. 3	2.3
	<i>V</i>	74. 4	1.5	80. 8	2.7	56. 0	2.2
	<i>R</i>	76. 4	1.3	84. 5	2.9	58. 9	2.0
	<i>I</i> 35" -315"	67. 5	1.1	74. 5	2.3	58. 5	1.5
NGC 4321	<i>B</i>	155.0	18.8	195.1	64.8	93.4	7.4
	<i>V</i>	109.9	6.6	137.7	18.0	76.4	4.6
	<i>R</i>	100.4	5.7	124.8	11.9	72.2	4.2
	<i>I</i> 35" -100"	86.3	4.2	106.5	5.8	65.8	3.5
NGC 4321	<i>B</i>	61.2	1.9	72.6	4.7	49.8	1.9
	<i>V</i>	69.1	2.2	80.9	5.6	46.3	2.2
	<i>R</i>	72.7	2.3	87.8	6.6	50.3	2.4
	<i>I</i> 100" -315"	63.5	1.7	76.0	5.0	51.3	1.7

3. Observational results

3.1. M 51

Fig. 1.— Contour representation of the photometric map of M 51 in the *B*-band. The boundary between the arms and the interarm region is shown as a thick contour (the criterion for this boundary is explained in the text).

In Fig. 4 (a) we show azimuthally averaged radial surface brightness profiles for the whole galaxy in the B , R , I , and K bands, in Fig. 4 (b) the corresponding profiles for the arm regions of the disk, and in Fig. 4 (c) the profiles for the interarm zones. The best fit to the exponential disk component is indicated in each figure. The fitted values of the observed disk scale-length are listed in Table 1 for each photometric band, as well as the limits of the radial ranges over which the fits were obtained. If we look at the scale-lengths for the disk as a whole, we see a modest change between the B and the K bands: a fall of some 25%, but this masks a major difference between the arms and the inter-arm zones. In the arms the B scale-length is longer than that in K by a factor of 1.6, whereas in the interarm disk the scale-lengths change very little over the whole wavelength range. This stronger trend of scale-length variation with wavelength in the arms almost certainly results from more dust there than in the inter-arm zones, and we will examine this below using our theoretical models for comparison. The whole disk scale-lengths are quite close to those in the interarm disk, which means that for M 51 the optical effect of the arms, in the bands observed, does not greatly distort the average scale-lengths.

3.2. NGC 3631

In Fig. 5 (a) we present the radial surface brightness profiles for this object in the B , V , R , and I bands, in Fig. 5 (b) we show the profiles for the arms only, and in Fig. 5 (c) for the interarm zones. The fitted values for the observed scale-lengths and the extrapolated on-axis surface brightnesses are given in Table 1. The scale-length behavior of NGC 3631 is qualitatively similar to that of M 51. In the arms there is a systematic decline of scale-length with increasing wavelength, which is barely evident in the interarm disk. The scale-lengths in the arms are systematically longer than those in the interarm zones, but converge towards equality as the wavelength increases. We do not have K-band information here, but in this convergence, NGC 3631 shows similarity to M 51. Here, too, the most straightforward interpretation of the trends observed is that in the arms the optical effects of dust extinction are readily detectable, whereas in the inter-arm zones they are not. We will use comparison with our models in the next section to quantify these considerations. As for M 51 the average scale-lengths for the whole disk of NGC 3631 are closer in value to those of the interarm zones. The outer parts of the profiles fall away more steeply than in the zone whose scale-lengths we have measured, but the signal to noise ratios are not high here, so scale-length measurements here would not be reliable, although we can obtain a rough indication of uniformity with wavelength.

3.3. NGC 4321

Figure 6 shows the radial photometric profiles of this galaxy: in Fig. 6 (a) the averages for the whole disk, in Fig. 6 (b) the profiles for the arms alone, and in Fig. 6 (c) those for the interarm zones. The fitted scale-lengths are again given in Table 1. There are notable differences in profile behavior between NGC 4321 and the other galaxies. In NGC 4321 the profiles divide clearly into two radial zones, from 35"

Fig. 2.— As Fig. 1, now for NGC 3631

to 100" from the center, and from 100" to 315". The inner zone corresponds to the bar reported, among others, by Pierce (1986) and studied photometrically and kinematically in Knapen *et al.* (1993), and the outer zone compares to the disk beyond the bar. We should note that our observations here go out to some 5 scale-lengths from the center, compared with only 3 scale-lengths for the other two galaxies.

The behavior of the inner zone is quantitatively similar to that of the disks of the other two objects. Both arm and interarm scale-lengths decline with increasing wavelength, as expected from systems containing measurable quantities of dust. The 'arm' scale-length is larger, and appears to be converging to a longer value than the interarm lengths, implying a slower fall-off in intrinsic stellar surface brightness in the arms (by no means unexpected).

The behavior of the outer zone is qualitatively different. Here too the arms show considerably longer scale-lengths, showing that the arm-interarm contrast is rising with increasing radius; this must be a property of the surface density of the stellar population. However there are no systematic trends to scale-lengths at longer wavelengths in this radial range. The interarm zone shows virtually no variation at all, while the arms show a slight increase from B to R , followed by a slight dip at I . In neither case is the behavior readily consistent with major quantities of dust, and we can conclude that there is relatively little dust in the outer parts of the disk of NGC 4321.

4. Comparison of observations with models: the role of dust

4.1. Tests for dust in spirals

There has been considerable discussion in the recent literature about the possible presence of major quantities of dust in galactic disks, and of the implications for the measured properties of galaxies, in particular for their mass to light (M/L) ratios. A variety of observational tests has been brought to bear on the problem. Valentijn (1990) used the variation of surface brightness with inclination angle for a large sample of galaxies taken from the ESO-LV catalog (Lauberts & Valentijn 1989), reaching the conclusion that disks must be optically thick in some agent causing extinction (not necessarily dust), because the surface brightness does not increase sufficiently with increasing inclination angle for an optically thin system. Valentijn's conclusions challenged the classical study by Holmberg (1958), who used the same test, and claimed clear evidence for low optical thickness in disks.

Absolute measurements of dust extinction have recently been published for a small number of nearly edge-on galaxies (Knapen *et al.* 1991; Jansen *et al.* 1994; Byun *et al.* 1994), with values of peak optical depths of between 2 and 3 in the central, densest parts of the dust lanes observed. Assuming that this dust is distributed in an exponential form, comparable to the stars or gas in a typical galactic disk, we would infer that the same galaxies, when observed face on, would exhibit optical depths in B or V well below unity over all but possibly the innermost parts of their disks. If on the other hand the dust is concentrated into narrow lanes the face-on optical depth of a lane might well be significantly higher than this but the optical depth averaged over the disk is very unlikely to be so.

Fig. 3.— As Fig. 1, now for NGC 4321

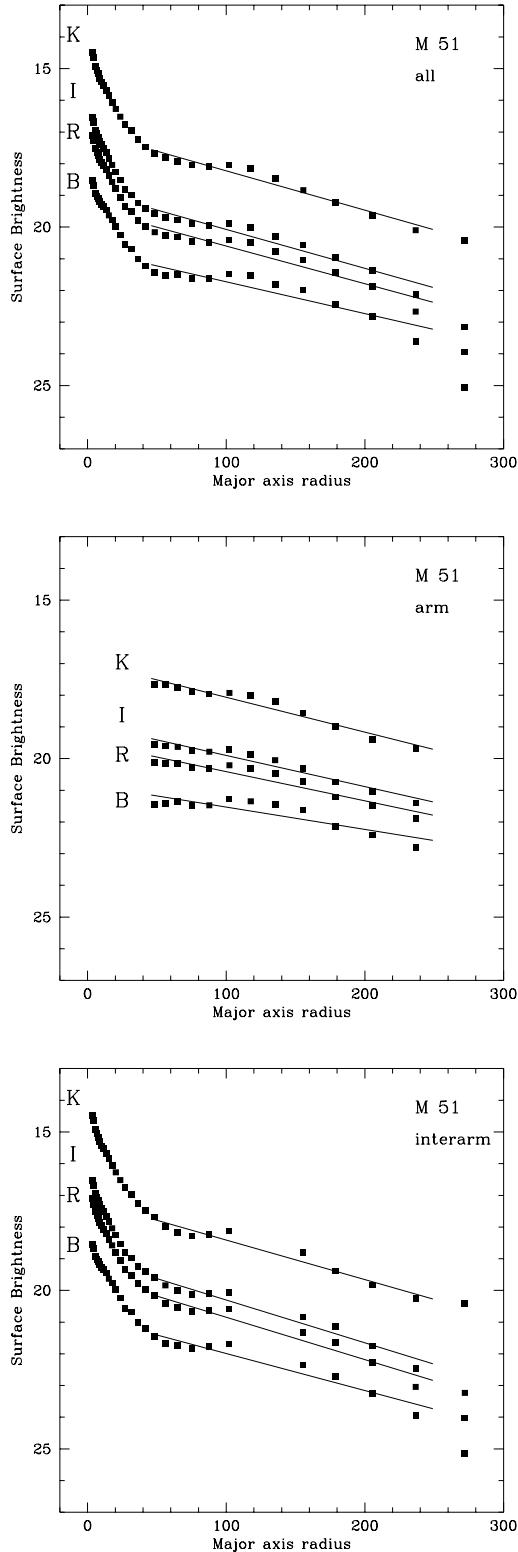


Fig. 4.— Radial surface brightness profiles for M 51 for the whole galaxy (a), the arms (b), and the interarm region (c). Also plotted are the exponential fits to the surface brightness profiles that best fit in the range over which the lines have been drawn.

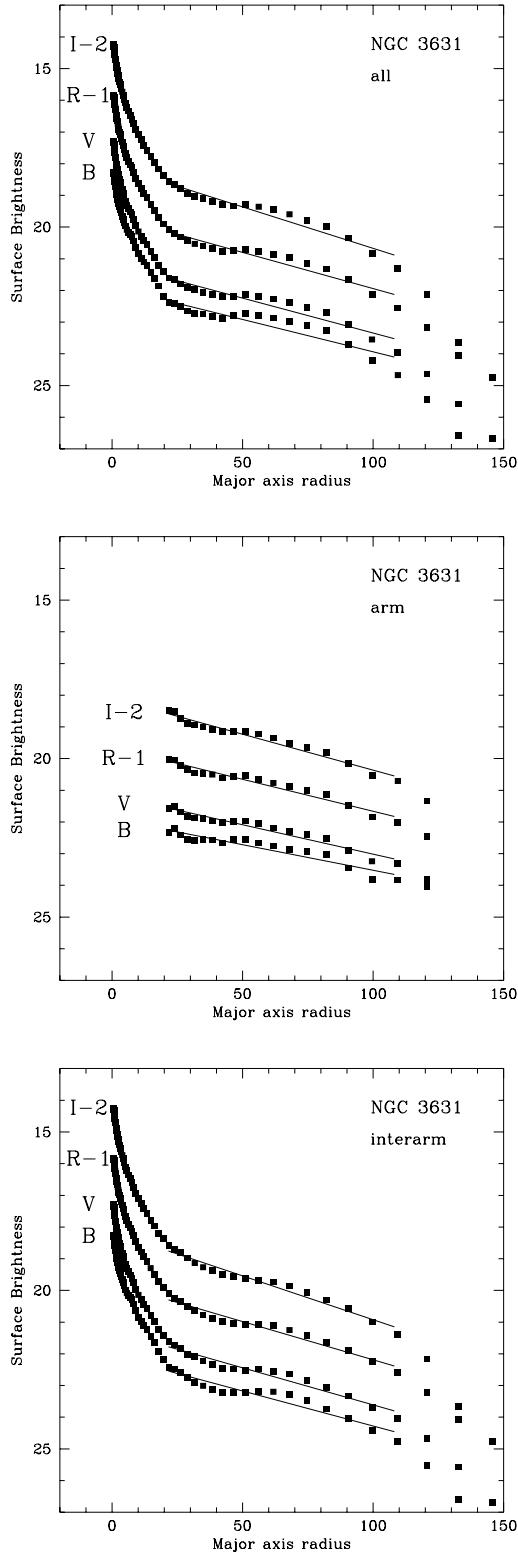


Fig. 5.— Radial surface brightness profiles for NGC 3631 for the whole galaxy (a), the arms (b), and the interarm region (c). Also plotted are the exponential fits to the surface brightness profiles that best fit in the range over which the lines have been drawn.

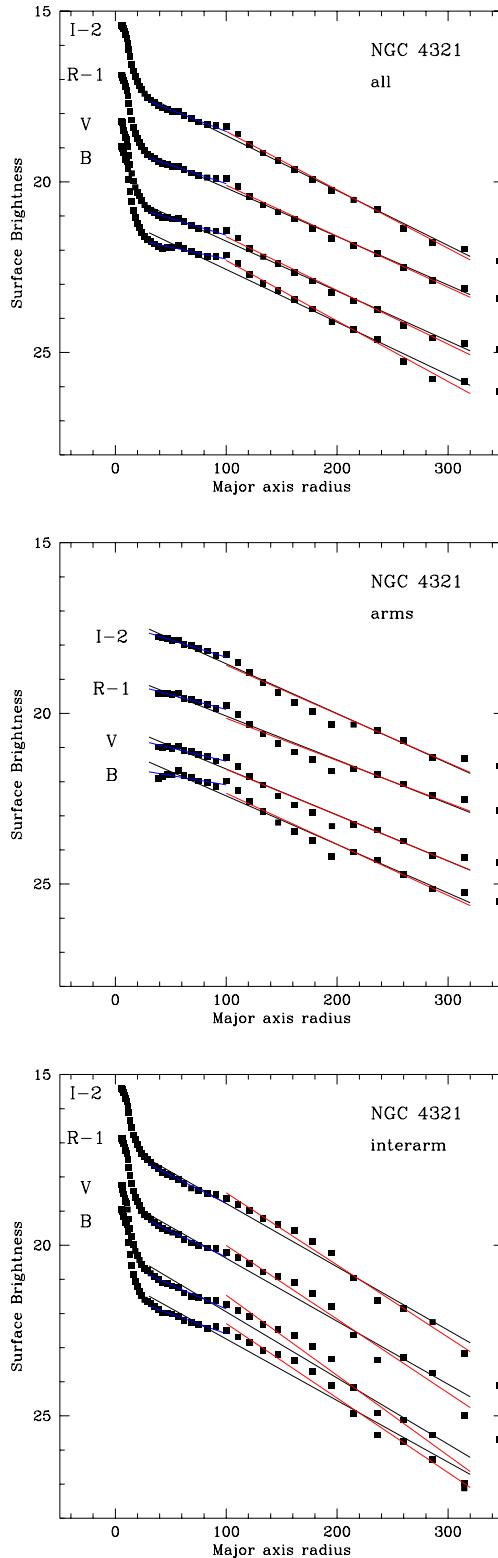


Fig. 6.— Radial surface brightness profiles for NGC 4321 for the whole galaxy (a), the arms (b), and the interarm region (c). Also plotted are the exponential fits to the surface brightness profiles that best fit in the range over which the lines have been drawn.

In a study of the surface photometry in B and K of 37 Sb's and Sc's, Peletier *et al.* (1995) found that the $B - K$ colors in the centers of the disks of spirals are generally more than 1 magnitude redder than at D_{25} . This, and the inclination dependence, implies that the extinction in the B band in the centers of face-on galaxies is generally of order 1 magnitude. However the dust morphology in galaxies is not monotonically exponential, as we have seen for the galaxies treated in the present paper, and the absolute extinction in edge-on objects could well be attributable to single dust lanes. If we assume this, and take the geometrical width of a dust-lane to be of the order of half the width of a spiral arm (see e.g. Plate 1), we would infer from the edge-on galaxy measurements that face-on dust-lane depths are indeed of order 2 or 3. We note again, however, that the optical depths over the rest of the disk are likely to be much lower.

Kinematic tests, using the wavelength dependence of the rotation curves of edge-on galaxies have been performed by Bosma *et al.* (1992), and by Prada *et al.* (1994, 1996). The former authors, combining radio and optical data, inferred low dust optical depths, at least in the outer parts of the Sc spiral NGC 100, and the Sb spiral NGC 891. The latter authors, using optical and NIR spectroscopy, found an optical depth of ~ 30 in the SABc galaxy NGC 253 and close to 10 along a line of sight close to the center of the Sb pec. galaxy NGC 2146. These values would translate to face-on values of resp. 3 and 1 for a homogeneous exponential dust distribution. Another test, which is revealing, but almost impossible to apply on a statistical basis, was used by Andredakis and van der Kruit (1992), who studied the colors of a galaxy seen through the outer parts of a disk of a nearer Scd galaxy, concluding that the foreground spiral was optically thin at the point of observation. In a similar observation White & Keel (1992) studied a galaxy seen behind a foreground Sbc galaxy and concluded that the nearer object exhibited significantly more extinction in the arms than between them. These measurements are consistent with the view of Valentijn (1990) that galaxies of type 3-5 (Sb-Sc) contain significantly more dust than Scd galaxies (type 6).

The differential scale-length test used in the present paper is potentially powerful, as it is susceptible to a statistical approach. In a disk with a uniformly distributed stellar population falling exponentially in surface density the observed scale-length will vary with wavelength, if there is a significant amount of dust. For dust obeying the same extinction law as in our Galaxy (see Knapen *et al.* 1992; and Jansen *et al.* 1994 for evidence that this is a reasonable assumption to take) the observed scale-length will decrease systematically with increasing wavelength in the presence of significant quantities of dust, also distributed exponentially. To illustrate the magnitude of the effect with an example, if the intrinsic radial surface density distributions of the stellar population and the dust follow the same exponential trend and the dust has a scale-height above the mid-plane of the galaxy one half that of the stars, the observed scale-length in the B band will be twice that in the K band for an on-axis extrapolated optical depth of 3 in B . The ratio of the B to I scale-lengths in this case would be 1.4 (see Peletier *et al.* (1995) for more examples). Differences of this order are not especially difficult to measure with the required accuracy, over the first 3 scale-lengths of a disk, if the area covered by the detector is large enough. Previous studies in which the scale-length as a function of wavelength has been presented, or whose radial color variations have been examined, include that by Elmegreen and Elmegreen (1984), Rix and Rieke (1993), Evans (1994), Peletier *et al.* (1994) and de Jong (1995). Of these, Rix and Rieke, Evans, Peletier *et al.* and de Jong offer interpretations explicitly in terms of dust extinction. In fact Evans drew the negative conclusion that the measurements available to him were not of sufficient quality to distinguish between major and minor quantities of extinction in dust. However, the importance of the morphological detail: the quantitative separation of arm and inter-arm disk, and the importance of the geometry of the structures in which the dust is distributed have previously been discussed only briefly by the present authors (Beckman *et al.* 1995) when considering large-scale extinction by dust in disk galaxies.

4.2. The Model

We have developed our own models for the transfer of radiation through disk galaxies, which take into account the effects of absorption and of multiple (diffuse) scattering by dust. In this respect they differ from the “triplex” models of Disney *et al.* (1989), although the basic scheme and underlying concept is owed to these authors. The radiative transfer equation was solved for a local plane parallel geometry, using a moment method with a high order closure relation for the moment system, in order to take into account the angular phase function of the dust. The moment system was solved using an implicit method which assures unconditional stability (Golulo & Ortega 1992). The algorithm will be presented in a forthcoming paper (Corradi, Beckman & Simonneau 1996, in preparation). The scattering phase function of Henyey and Greenstein (1941) was adopted throughout, and the dust parameters: opacity, albedo, and the scattering anisotropy parameter, were taken from Di Bartolomeo *et al.* (1995). These models were used as first order approximations to the disks of galaxies observed face-on ($i = 0$). Axisymmetric exponential distributions of stars and dust are assumed, in two perpendicular dimensions which represent the radial and axial directions, R and z , respectively, as expressed in equations (1) and (2):

$$\epsilon(R, z) = \epsilon(0) \exp^{(-R/R_s - z/z_s)} \quad (1)$$

$$\alpha(R, z) = \alpha(0) \exp^{(-R/R_d - z/z_d)} \quad (2)$$

where (R, z) are cylindrical coordinates, $\epsilon(R, z)$ is the volume emissivity of the stellar contributors, $\alpha(R, z)$ is the dust opacity, and R_s , z_s and R_d , z_d are the scale-lengths and the scale-heights of the stars and the dust, respectively. In order to limit the number of free parameters, we have assumed in the present exercise that the stars and the dust have the same radial scale-lengths i. e. that $R_s = R_d$. These one-dimensional models describe correctly the exponential variations of the volume emissivity and the opacity in the direction of the z -axis of a disk, and variable values can be incorporated for the stellar to dust scale-height ratio. The plane-parallel geometry does not, of course permit a perfect representation of the radial exponential decline in the disk. To account for this we make the approximation that at a given radius R the galaxy can be treated as a plane-parallel system, with $\epsilon(R, z)$ and $\alpha(R, z)$ given by eqs. (1) and (2). This approximation is valid, given the large ratios of scale-length to scale-height in the disks of galaxies, if the mean free path of a photon is short compared with the scale of the variation of the volume emissivity. This condition does not strictly hold for low optical thicknesses, i.e. at large radii or for large heights above the planes of galaxies, but the present models nevertheless can give valuable insight into the effects of dust extinction (and in particular of the effect of scattering) on galaxy photometry.

We will show here results obtained using two modes of the models: one in which the scattering albedo was set to zero, i. e. with absorption only, and the full model with the same opacity but with realistic scattering parameters included. We note that in the first case the models in fact yield the exact solution of the radiative transfer equation for a face-on system. The models run for comparison with the observations presented in the present paper were for a range of galactocentric distances out to 5 intrinsic scale-lengths, and used two ratios of stellar to dust scale-height ratios: 1 and 3, to comply with a range of observationally observed dust distributions seen in edge-on systems (see Jansen *et al.* 1994). The models were parametrized in terms of their central optical depth (i. e. the optical depth extrapolated to the central axis of the disk) in the V band τ_V ($= 2\alpha(0) z_d$) and the corresponding values of τ for the other photometric bands were scaled from the dust opacities in Di Bartolomeo *et al.* (1995) based on the Galactic extinction law

(Rieke & Lebofsky 1985). The models were then run for the bands B V R I and K according to the observational data to be fitted for each galaxy. The direct outputs from the models are a set of theoretical radial luminosity profiles for the dusty disks. The associated scale-lengths are then computed by taking a linear fit to the logarithmic representation of the intensity of the profile between selected inner and outer radii. In general a disk with a truly exponential distribution of stars and dust does not yield an exponential intensity profile, but the deviations are not large, and decrease with increasing radial range. In consequence there will be a dependence of the derived scale-length on the values chosen for the radial limits in a given model. Here we have adopted the simple procedure of choosing, for a given galaxy, the same values for the radial limits in our models as those used in practice for deriving the observed scale-lengths. These limits are noted in Table 1.

4.3. The model fits

4.3.1. $M\,51$

In Fig. 7 we present the results of fitting the models described in Section 4.2 to the data in Table 1 for the case of $M\,51$. The 4 model fits shown are: 7 (a) and 7 (b) for dust with absorption only, no scattering, and with two different ratios of stellar to dust scale-heights: 1 and 3 respectively; 7 (c) and 7 (d) incorporate scattering for the same two ratios of stellar to dust scale-heights. In all 4 diagrams the observational data are shown in the form of ratios, normalized to the scale-length of the galaxy as a whole at the longest waveband used (K band). The wavelength dependence, stronger in the arms than in the interarm zone, is readily seen, and the values for the whole disk lie closer to those for the interarm zone. For comparison we include in each diagram the theoretical curves for 5 values of the central, visual optical depth τ_V (extrapolated to the central axis) of the galaxy. The values selected for τ_V are 1, 2, 4, 10 and 20. These comparisons yield the qualitative conclusion that the optical depth in $M\,51$ has moderate on-axis values. In Fig 7 (d), the case favoring most dust, the optical depth in V in the arms, extrapolated to the axis, takes a value of 10, and that in the interarm disk a value close to 1, and that of the galaxy as a whole a value between 2 and 4. This assumes that the scale-height in dust is only one third that of the stars, which is a conservative assumption as far as the young stellar component is concerned, and leads to a slight over-estimate of dust absorption. The value of the optical depth averaged out to a radius of 3 scale-lengths from the center would be 0.7. These values in fact give an intuitively false, exaggerated idea of the effective light absorption, because we are used to situations - those within our Galaxy- where the star or stars observed are all behind the absorbing dust, a so-called “screen” situation. In fact, in the model represented in Fig 7 (d) for the whole disk the fraction of the light in V intercepted by dust, averaged out to a radius of 3 scale-lengths, is only 12%, and that is the relevant number to bear in mind when asking whether or not the dust in $M\,51$ could lead to a bad underestimate of the total stellar content. In fact the model stellar to dust scale-height ratio of 1 (Fig. 7c) gives better looking fits to the data than that for ratio 3 (Fig. 7d), but we have used the numbers for the latter case as being more conservative in giving a greater amount of dust extinction.

4.3.2. $NGC\,3631$

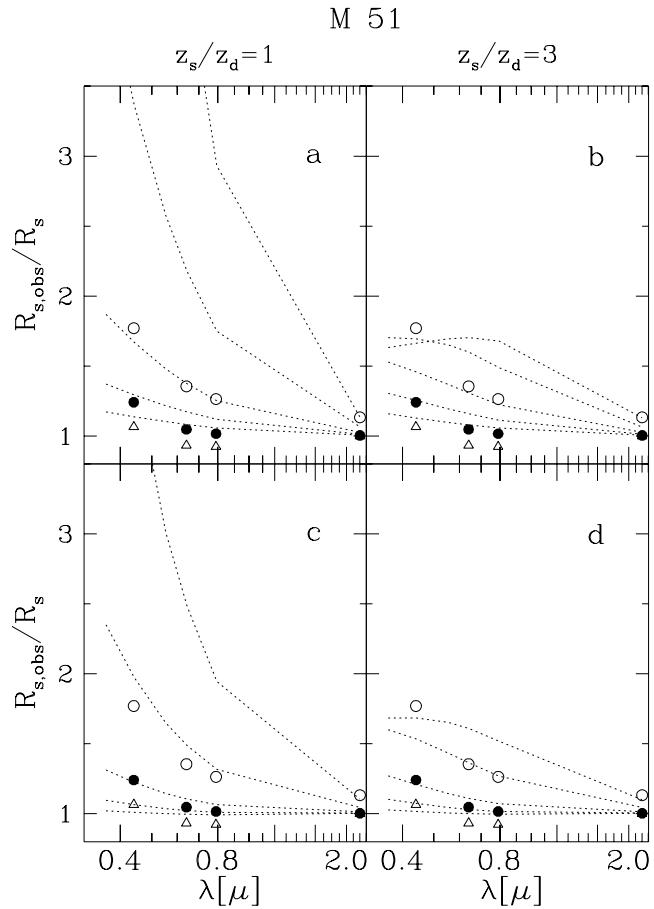


Fig. 7.— Scattering models of M 51. Plotted are scale-length ratios for the interarm region (open triangles), the arms (open circles) and the whole disk (filled circles), together with model curves for $\tau_V = 1, 2, 4, 10$ and 20. The upper models include absorption only, while the lower models include absorption and scattering.

The model fits to the data for NGC 3631 are shown in Fig. 8. Equivalent cases are dealt with to those shown for M 51, i. e. absorption alone, and absorption plus scattering, for the two ratios, 1 and 3, of the stellar to dust scale-height ratio. Here again the pure absorption cases requires a lower optical depth in dust than the scattering cases, but we treat only the latter as serious candidates for good model fits, since real dust must in fact show scattering. The general behavior of the arms, the interarm zones, and the averaged disk is quite similar, in this galaxy, to that of M 51, and the scattering models in Figs 8 (c) and 8 (d) give very fair fits to the observations, when the on-axis V-band optical depth for the arms takes the value 10; for the interarm zones the corresponding value is close to 4, and for the galaxy as a whole the best value is 6. The average value for the dust optical depth in V out to a radius of 3 scale-lengths is 1.1 for this galaxy. We should note that this average (as for M 51), is taken over the disk, but extrapolated to cover the innermost zone, occupied by the bulge, so that the value 1.1 represents an upper limit. The bulge really ought to be excluded from present considerations. This would have implied averaging between 0.3 scale-lengths and 3 scale-lengths to get a true disk estimate. Giving τ_V this conservatively high mean value of 1.1, however, we find using the corresponding flux integration that no more than 20% of the light in the disk, out to 3 scale-lengths from the center, has been removed by dust. Just like in the case of M 51, the star to dust scale-height ratio of 1 appears to give better fits to the data than the ratio 3; here too we have preferred to use the latter model to quantify the dust, in order to over- rather than underestimate the extinction.

4.3.3. NGC 4321

In NGC 4321 we have seen that the disk is clearly divided into an inner zone with monotonic wavelength variations for the scale-lengths in the arms and the interarm regions, and an outer region, where there is no systematic variation. In Fig. 9 we show the model fits for the two values of the stellar to dust scale-height ratio; 3 and 1, and for dust with and without scattering, as applied to the inner zone. It is clear from these Figures that for stellar to dust scale-height ratio 3 the models are not able to fit the data, whereas for a ratio of unity, fits are possible. We opt for the scattering case, Fig. 9c, as physically more realistic, and find that the optical depth in the arms has an on-axis extrapolated value of 8, the equivalent for the inter-arm zone is close to 3, and for the averaged disk 6. The radial extent of this zone is approximately the same as its own scale-length, and the estimated fraction of light removed by dust is some 40 % in this zone.

The outer zone is much more difficult to quantify, as the observed scale-lengths do not give fits to the models, showing that one or more of the model assumptions does not hold (See Fig. 10). The interarm disk is characterized by essentially invariant scale-lengths, while the arms show slightly larger scale-lengths in V and R than in B and I , but all within a 20% range of values, and all some 50-60% longer than the interarm values. Our judgement about these results is that the basic difference between the arm and the interarm values is due to the fact that the arms have a stellar population distribution with a shallower radial slope i.e. the arm-interarm contrast in stellar surface density rises with increasing radius. The fine detail in R and I in the arm values is probably due to the effects of radial star formation differences on the arm population, but this speculative and not of prime importance for the present study, and we will not pursue it further here. A zero order conclusion about the dust in the outer zone is that there is very little in the interarm zone. This conclusion is very clear, if we exclude an exact cancellation of dust reddening and population blueing as the cause of the wavelength-invariance of the scale-lengths. In the arms it is also a measurable inference. The outer disk clearly dominates when we fit the whole range of the galaxy between 35" and 315", as we see in Fig. 11, so that the behavior here qualitatively is the same as in Fig. 10. We will discuss below in detail the possible effects of dust in lanes, rather than distributed uniformly exponentially.

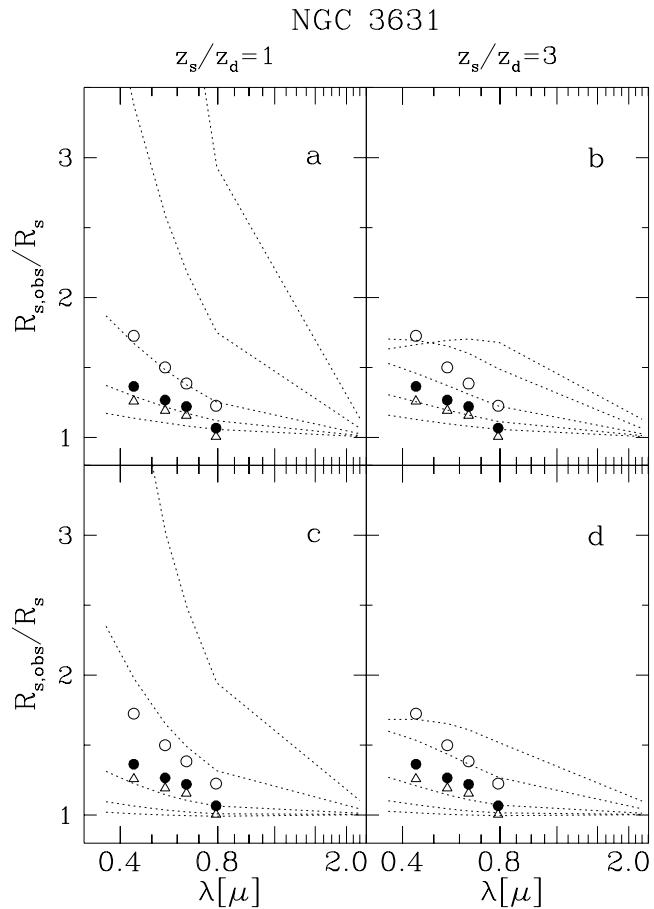


Fig. 8.— Scattering models of NGC 3631. Plotted are scale-length ratios for the interarm region (open triangles), the arms (open circles) and the whole disk (filled circles), together with model curves for $\tau_V = 1, 2, 4, 10$ and 20. The upper models include absorption only, while the lower models include absorption and scattering.

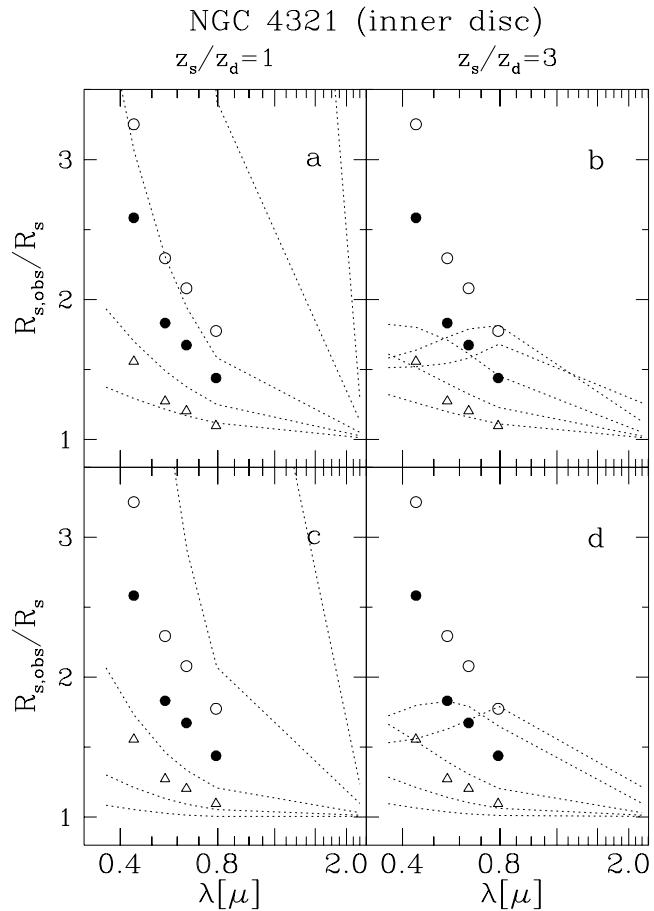


Fig. 9.— Scattering models of NGC 4321 for the inner range. Plotted are scale-length ratios for the interarm region (open triangles), the arms (open circles) and the whole disk (filled circles), together with model curves for $\tau_V = 1, 2, 4, 10$ and 20 . The upper models include absorption only, while the lower models include absorption and scattering.

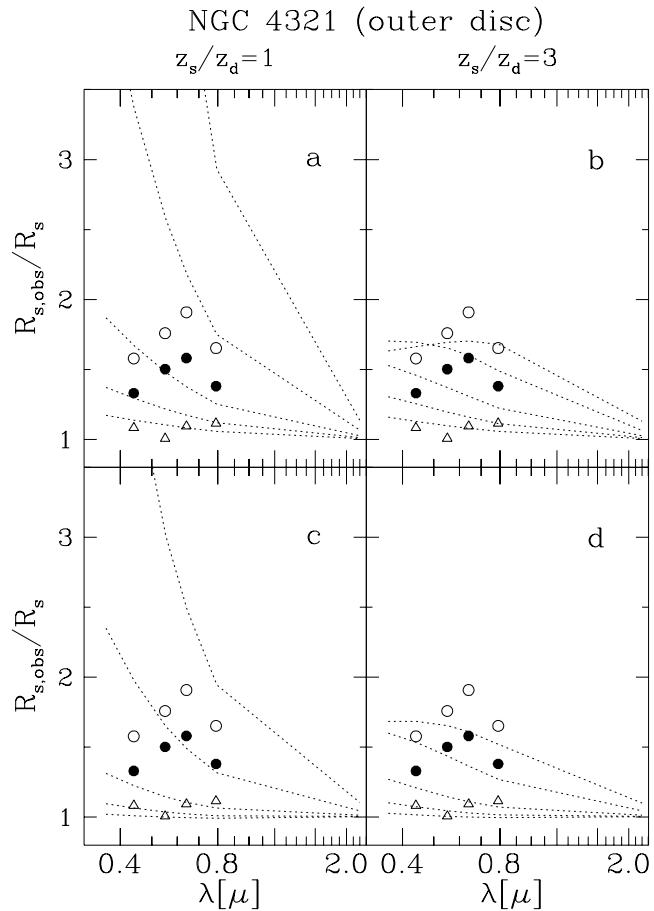


Fig. 10.— Scattering models of NGC 4321 for the outer range. Plotted are scale-length ratios for the interarm region (open triangles), the arms (open circles) and the whole disk (filled circles), together with model curves for $\tau_V = 1, 2, 4, 10$ and 20 . The upper models include absorption only, while the lower models include absorption and scattering.

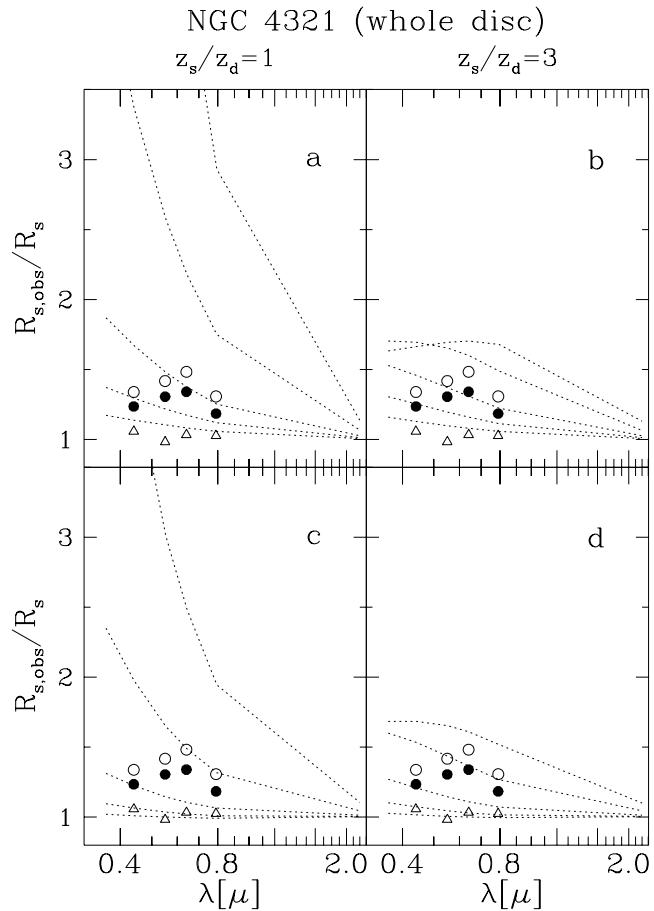


Fig. 11.— Scattering models of NGC 4321 for the whole disk. Plotted are scale-length ratios for the interarm region (open triangles), the arms (open circles) and the whole disk (filled circles), together with model curves for $\tau_V = 1, 2, 4, 10$ and 20. The upper models include absorption only, while the lower models include absorption and scattering.

5. Discussion and Conclusions

We have obtained azimuthally averaged radial intensity profiles in the B through I photometric bands, of three nearby spiral galaxies: M 51, NGC 3631, and NGC 4321; for the first of these we also obtained a profile in the K band. As the arms and the interarm disk zones are manifestly different photometrically, we went on to derive separate profiles for the two types of zone in each galaxy, and measured the radial intensity scale-lengths, separately, for the arms, and the interarm zones, as well as for the galaxy disks as a whole. The results for M 51 and NGC 3631 show scale-lengths which decline systematically, but not steeply, with increasing wavelength, and arm scale-lengths which are longer than the interarm scale-lengths at short wavelengths, but converge to the interarm values at longer wavelength. For NGC 4321 we find an inner zone which behaves in the same way as the disks of the other two objects, and an outer zone which contains less dust. However, our observations go out further for NGC 4321, and we might well expect similar results in the outer parts of the other two objects. We have interpreted these results using radiative transfer models which take into account scattering as well as absorption by dust. We characterise the dust distribution by an integrated optical depth, τ_V along the central axis of the disk, as well as by a vertical scale-height, and an intrinsic radial scale-length. Since τ_V is a quantity extrapolated inwards to the axis, it represents an upper limit to the values found everywhere in the disk. For M 51 the best model fits to the observed scale-lengths yield values for τ_V of close to 10 for the arms, close to 1 in the interarm disk, and a mean of 3 over the disk as a whole. The corresponding values for NGC 3631 are 10, 4, and 6 respectively.

As well as being upper limits these values yield a misleadingly high impression of the effect of the dust extinction because we tend to think of an optical depth in terms of the most familiar scenario in our own Galaxy where the source lies entirely behind the absorbing dust cloud. The τ_V in the models used here is an integrated value through the center of the (extrapolated) disk, but the stars and dust are distributed throughout the disk, so the net absorption will be much lower than if all the dust were between us and the stellar component. As an example for $\tau_V = 5$ (the on-axis value), and a stellar to dust scale-height ratio of 1, the dust extinction for the absorption + scattering case for the face-on system along its axis is 60% of the total light. For a “screen” model (all the dust in front of the stars) the equivalent would be 99%. The corresponding figures for a stellar to dust scale-height ratio of 3 are 50% and (of course) 99% respectively. We may also include, for comparison, models with pure absorption and no scattering. For $\tau_V = 5$ and the scale-height ratio 1, extinction would take out 80% of the light, and for a scale-height ratio 3 this would be 67%. These figures are larger than those for the models including scattering, but they should not be taken as representative of real dust. It is also instructive to make a further calculation: of the fraction of light removed by dust averaged over the disk. To be specific, we have integrated the transfer equations out to 3 scale-lengths from the axis. Setting $\tau_V = 5$ and with the stellar to dust scale-height ratio unity, we find that only 15% of the total flux has been removed by dust, this figure is virtually unchanged if we change the scale-height ratio to 3. It is notable that in a screen scenario the figure would be 70%. From the numbers presented in the previous paragraph we can conclude that the light extinguished in M 51 and in NGC 3631 by the presence of dust in their disks will be of order 15% of the total starlight emitted. The qualitative conclusion is that, for these two galaxies, it is most unlikely that a major fraction of their light is being extinguished by interstellar dust.

A further consideration to be taken into account is the non-uniformity of the geometrical distribution of the dust, notably its compression into lanes. It is clear from any image of typical disk galaxies, such as those in Plate 1, that the dust is in fact concentrated in lanes, especially prominent along the edges of the spiral arms, where the gas is being compressed by the passage of a density wave. We have run models to test for the effects of a dust lane on the scale-length of (say) an arm. To first order we find that a dust

lane which occupies a fraction x of an arm, with the rest of the arm dust-free, yields the same effect on the scale-length as if the whole arm were characterized by an optical depth τ_V , provided that the on-axis extrapolated optical depth of the dust-lane is τ_V/x . A modeled lane occupying only 30% of the surface of an arm will give essentially the same averaged photometric arm profile as if the arm had dust uniformly distributed across its surface, but the dust lane requires some 3 times the on-axis optical depth as the uniformly dusty arm. These considerations will be dealt with in more depth in a paper devoted purely to the modelling technique. However we can infer here that the organization of the dust into lanes, and the details of such non-uniformities, would not alter the qualitative conclusion that there is only moderate to low net visible extinction across the disks of M 51 and NGC 3631. One should note that a somewhat similar technique to measure the amount of extinction was used by D. Elmegreen (1980). She used UBVRI colors of dusty regions in the disk of a few face-on spiral galaxies, and compared them with nearby regions without much dust. Applying a radiative transfer code that includes absorption and scattering she found values for the visual absorption of 0.3 – 1.2 mag in the interarm region, and 1.5 – 4 mag in the arms. These values are consistent with what we find here. The difference here is that we also require that the radial density distribution of the dust is exponential, which means that the models are somewhat better constrained.

The results for NGC 4321 are more complicated because a more extended part of the disk has been observed. In the inner disk, we find similar results to those of the other two galaxies. The measured scale-lengths, both in arms and interarm zone, decrease with increasing wavelength, but the systematics can be well modeled using dust. The outer disk is best described as a system low in dust, and in both inner and outer disk the arms show longer intrinsic scale-lengths than the interarm zone, as might be predicted from the active star formation evident in the arms. It would also be possible to take into account a fractional dust-lane cover in the inner zone of NGC 4321 in just the same way as that described above for M 51 and NGC 3631, and with a similar conclusion.

The overall results of the observational study presented here are thus:

- It is feasible, valuable, and physically instructive, to separate the arm regime from that of the interarm disk when measuring the radial luminosity profile of a disk galaxy, and to extract separately the respective scale-lengths, whose wavelength dependence is to be analyzed. In general the arm scale-lengths are longer than those of the interarm zones.
- In two of the three slightly inclined galaxies observed we find a simple coherent picture of the wavelength dependence of the scale-lengths in terms of dust extinction. The dust optical depth is measurably greater in the arms than in the interarm disk, a not unexpected result. Our model fits imply that the dust removes less than 20% of the emitted starlight in the V band from those portions of the disks within two intrinsic scale-lengths from the axis (at greater radii this figure would be even lower). In the third galaxy, where we have been studying a greater radial range, the inner disk shows similar dust properties to the disks of the other two galaxies, while in the outer disk the most reasonable interpretation of the results is that there is not enough dust to have a significant effect on the scale-lengths.
- The results would remain essentially the same if we assumed that the dust was compressed into lanes occupying a fraction x of the surface area of the zone under consideration, with axial optical depth greater by a factor $1/x$ than for the uniform case.
- Better fits of the scale-length vs. wavelength observations are obtained for models with stellar to dust scale-height ratio of 1 rather than 3, notably for the arms. This tentative result would be most interesting to confirm with a broader data base.

The present study should be seen as a trial in two senses. Firstly we have measured only three objects: one Sbc galaxy, and two Sc galaxies. There are observational reasons to believe that there may be less dust in later-type galaxies, and any work aimed at drawing statistical conclusions should have a more representative base, simply in terms of numbers of objects, but also in terms of the spread of morphological types. Secondly we have not explicitly taken into account radial variation in the intrinsic colors of the stellar populations. The fact that the observed radial color variations are small in these objects suggests strongly that such stellar effects are not important here (ruling out the fortuitous cancellation between dust reddening and stellar population blueing as a function of radius), but any tendency of the stars in the outer parts of disks to be bluer would tend to make us under-estimate the dust content. Here again, with a wider data set, where comparisons between galaxy types can be made, we may obtain a clearer idea of how well such population effects can be quantified. In spite of these limitations, we feel that we have shown, in this article, how the scale-length test may be employed with considerable value as a dust diagnostic in disk galaxies.

This paper is based on observations obtained in service time at the Isaac Newton Telescope and the Jacobus Kapteyn Telescope at La Palma, operated by the RGO at the Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. We thank H.-W. Rix for making available to us the images of M 51. This work was partially supported by grants PB91-0510 and PB94-1107 of the Spanish DGICYT. The work of CRLM is supported by a grant of the EC Human Capital and Mobility Program.

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